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DAYLIGHT AVAILABILITY DATA FOR SAN FRANCISCO

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ABSTRACT

This paper analyzes solar radiation and daylight measurements taken during a four-year period in San Francisco, California. Horizontal and vertical surface measurements were taken by nine sensors at 15-minute intervals under all sun and sky conditions. The data base from which results were derived exceeds 400,000 measurements.

Equations are derived for clear sky global, direct, and diffuse illuminance and irradiance on a horizontal surface as a function of solar altitude, and for overcast sky horizontal illuminance and irradiance. We present the standard deviations for all parameters in our equations to show the scatter in our data. The average illuminance on horizontal and vertical surfaces by hour and by month are presented as isolux contour plots. These data are also displayed as probability distributions, showing the percent of time in a year that a given irradiance or illuminance value will be exceeded. Monthly average values of sunshine probability are determined and compared to long-term NOAA data.

INTRODUCTION

Daylight availability data are essential for designing effectively daylighted buildings. These data not only provide the basis for specifying illuminance on a given surface at a specific time, day, and location, but also describe 1) maximum and minimum illuminance conditions on vertical and horizontal surfaces, 2) clear and overcast sky design illuminance values, 3) average illuminance conditions (hourly data for months or seasons), 4) probability of a given illuminance value and the cumulative probability that a given value will be exceeded, and 5) correlation of illuminances to irradiance values. Not all types of data are required for each purpose--however, each type provides specific, useful information to help solve a particular design problem. In many cases approximate data will suffice, but it is important that simple algorithms and correlations be derived from a broad empirical data base.

Although a number of researchers have reported results of availability studies in Australia, Japan, South Africa, and several European countries (see for example Refs. [1] through [4]), data for the United States are scarce. Although limited measurements were made in the 1920s [5] and in the 1950s [6, 7], only in the past few years have systematic measurements of daylight availability been made in several U.S. locations [8]. Although theoretically derived algorithms for availability can be developed, measured data from various climates are needed.

As part of a broader research program to investigate the energy-saving potential of daylighting, we began collecting daylight availability data and related solar radiation data in San Francisco in 1978. The station has been in continuous operation since then and has provided useful data for more than 80% of this time (the 20% loss is due to hardware failures). These data form the basis for a detailed study of illuminance characteristics in the San Francisco Bay Area and provide a data base from which various algorithms and equations for availability have been developed and tested. Together with analysis of results from other U.S. and international locations, these data can begin to form the basis for standard availability data for the U.S.

DATA COLLECTION

San Francisco is situated at 38° north latitude, 123° longitude within the Pacific time zone. Data were collected on top of the Pacific Gas and Electric (PG&E) building in the city's financial district at 140 m (450 ft) above sea level. The station is located on a peninsula that separates the large San Francisco Bay from the Pacific Ocean. There is a wide range of local climatic conditions in the Bay Area. The most distinctive climatic characteristic of San Francisco is the low cloudiness and persistent morning fog along the western (Pacific Coastal) side of the city. The station experiences periods of substantial direct sunlight mixed with rapidly changing cloud conditions.

The instrumentation at the station consists of seven illuminance sensors (see Fig. 1), of which two measure total and diffuse illuminance on a horizontal plane (E_{lg} and E_{ld}), and four measure global vertical illuminance (with no ground contribution) at each cardinal orientation ($E_{lg-n,s,e,w}$). The seventh was especially adapted as a luminance sensor for zenith luminance measurements (L_z). There are two pyranometers for measuring global and diffuse irradiance on a horizontal surface (E_{eg} , E_{ed}). On the northwest side of the sensors is an antenna tower that obstructs a small portion of the sky (see Fig. 2). A time-lapse movie camera records the vertical south-facing view of the sky, a clock, and the instrument cluster. Measurements are taken at 15-minute intervals from before sunrise to after sunset. In order to eliminate ground-reflected light at the four vertical photometers, a horizontal, circular black honeycomb plane is

mounted below the sensors.

Data from the nine sensors were recorded on a magnetic tape at the building site. The tapes were transported to Lawrence Berkeley Laboratory (LBL) at weekly intervals, and the data read into the LBL computer system, which converted them to engineering units and processed them, to identify missing or erroneous data. The final tape of processed data formed the basis for all subsequent analysis. The data flow is shown in Fig. 3.

RESULTS

As part of our study, the area's ground-reflectance characteristics were examined under many typical clear and overcast sky conditions. Vertical illuminance measurements were taken with and without the ground plane; then the ground luminance for each orientation was measured. Calculations of ground reflectance from each method were in good agreement. The study shows that under typical conditions the effective ground reflectance for a clear day is 13%, and for an overcast day 18%.

Diffuse and global illuminances (and irradiances) were measured with shaded and unshaded sensors. The direct solar component was calculated by subtracting the diffuse values from the global using the techniques described in Ref. [9] to adjust for the effect of the shadow band. The vertical illuminance sensors measured the global values without ground contributions. Diffuse illuminance on a vertical surface was determined by subtracting the calculated direct solar component on the vertical surface (as calculated from horizontal measurements) from the measured global values.

The data were used to generate a series of equations, graphs, and tables that show global, direct, and diffuse illuminances and irradiances on horizontal and vertical surfaces. These data are representative of San Francisco climatic conditions. However, by correlating the measured data with basic atmospheric parameters such as turbidity, it should be possible to calculate daylight availability in other locations. The dependence of observed values on turbidity is described in more detail in companion papers [10, 11].

Clear sky irradiance and illuminance

Much of our analysis concentrated on clear sky conditions. Figures 4 and 5 show the average clear sky values of horizontal irradiances and illuminances for the four-year period of measurement. The maximum average global illuminance on a horizontal surface for the entire period is 104 kilolux (klx); the corresponding maximum average irradiance is 980 watts per square meter (W/m^2). The maximum average diffuse (sky) illuminance is 14 klx, and the maximum average irradiance 107 W/m^2 . The difference between the relevant values gives the direct beam component on a horizontal surface. Note that these are average values; instantaneous measurements are higher.

The distinction between cloudy and clear sky can be made and recorded visually, photographically, or with the aid of a Campbell-Stokes sunshine recorder. Fully automated photometric sensors and data recorders do not allow for conventional distinctions between sky conditions. The World Meteorological Organization (WMO) has defined direct beam sunshine as existing for a period of time (hour, day, month, year) during which the direct beam radiation on a plane normal to the sun equals or exceeds 200 W/m^2 . This value corresponds to the minimum irradiance required to scorch the card of a Campbell-Stokes sunshine recorder [12].

Consequently, we assume that if the normal irradiance exceeds 200 W/m^2 for a period of time, the sky conditions for that period are clear, and both direct and diffuse (sky) components exist. Continuous readings of lower levels indicate that the sun is obstructed and sky conditions are cloudy or overcast.

In the analysis that follows we use the WMO criteria to define clear sky data. When we compare Figs. 4 and 5 with those of other locations in the U.S. [8] and Europe [13], we find that our curves for diffuse sky illuminance and irradiance are similar to those of others. However, it should be noted that all the equations discussed here are availability models, which represent mean clear sky conditions useful for design calculations. They may not be good predictors of instantaneous values.

A series of equations has been developed for global, direct, and diffuse (sky) illuminance and irradiance for clear sky conditions as a function of solar altitude (γ_s). These equations do not explicitly account for any other variables because solar altitude is often the only quantity to which designers have easy access.

The following equations were derived by means of proportionally weighing the data in a least-squares curve-fitting procedure. We chose the same general format for the equation as was used previously by a number of investigators [8]:

$$F = A_1 + A_2 \sin^{A_3}(\gamma_s) . \quad (1)$$

The following are the derived equations for global, direct, and diffuse illuminance as well as irradiance on a horizontal surface:

$$E_{lg} = 0.927 + 117.2 \sin^{1.325}(\gamma_s) \text{ (global illuminance, klx)} \quad (2)$$

$$E_{lcl} = 0.586 + 14.56 \sin^{0.615}(\gamma_s) \text{ (diffuse illuminance, klx)} \quad (3)$$

$$E_{lsh} = 0.106 + 113.8 \sin^{1.75}(\gamma_s) \text{ (direct illuminance, klx)} \quad (4)$$

$$E_{eg} = 13.1 + 1060 \sin^{1.31}(\gamma_s) \text{ (global irradiance, W/m}^2\text{)} \quad (5)$$

$$E_{ecl} = 5.9 + 110.8 \sin^{0.75}(\gamma_s) \text{ (diffuse irradiance, W/m}^2\text{)} \quad (6)$$

$$E_{esh} = 7.6 + 977 \sin^{1.47}(\gamma_s) \text{ (direct irradiance, W/m}^2\text{)} \quad (7)$$

The standard deviation for each parameter within each function is given in Table 1. We also provide the standard deviation for each fit.

Table 1.

Function	Parameter			Overall fit
	A_1	A_2	A_3	
E_{lg}	0.127	1.938	0.0218	0.07
E_{lcl}	0.200	0.213	0.0284	0.05
E_{lsh}	0.097	5.468	0.0595	0.21
E_{eg}	0.918	12.87	0.0174	0.05
E_{ecl}	1.210	1.657	0.0317	0.06
E_{esh}	1.080	22.60	0.0328	0.09

Overcast sky conditions

We derived an equation for average overcast sky illuminance as a function of solar altitude. Analysis of our data indicated that sky conditions could be defined as overcast when the direct beam irradiance is less than 20 W/m^2 and the ratio of diffuse to global irradiance is greater than 0.67. Figure 6 shows average overcast sky illuminance (E_{loc}) as a function of solar altitude. The average overcast sky irradiance (E_{eoc}) behaved similarly as a function of solar altitude. The relationship between E_{loc} , E_{eoc} and the solar altitude, γ_s (in degrees), can be represented by a simple linear function of the form $F = A_1 + A_2 \gamma_s$:

$$E_{loc} = 0.357 + 0.578 \gamma_s \quad (\text{overcast illuminance, } klx) \quad (8)$$

$$E_{eoc} = 2.9 + 4.60 \gamma_s \quad (\text{overcast irradiance, } W/m^2) \quad (9)$$

The standard deviation for each parameter and each fit is given in Table 2:

Table 2.

Function	Parameter		
	A_1	A_2	Overall Fit
E_{loc}	0.067	0.008	0.07
E_{eoc}	1.08	0.111	0.11

Average sky conditions

Hourly and monthly average illuminance values are commonly used during the design process. We averaged our data with and without direct sun for both horizontal and vertical surfaces (facing the four cardinal orientations). Isolux contour plots of these variables are presented in Figs. 7 through 12. These plots are a result of bi-weekly and hourly averages of our data under all sky conditions. The irregularities in the contours for late summer afternoons are due to shadows cast by the communications tower (see Fig. 2) during this period. The effect is most obvious for the west vertical data (Fig. 12).

An isolux contour plot can be used to predict the time periods for which average illuminance will exceed a specified value. Our measurements also make it possible to evaluate the cumulative probability distribution, which shows the percent of time that each illuminance value is equaled or exceeded. Figures 13 and 14 show the probability distribution of horizontal global and diffuse sky irradiance and illuminance for all sky conditions. Figure 15 gives the probability distributions for the vertical illuminance on the four cardinal orientations. These are particularly useful for predicting the annual energy savings to be expected from using lighting controls in daylighted buildings that have horizontal or vertical glazing.

Sunshine probability

Sunshine probability data are often used as the basis for a variety of other derived solar parameters. Figure 16 shows long-term monthly data from the U.S. National Oceanographic and Atmospheric Administration (NOAA) [14] and monthly average values of sunshine probability derived from our data using two different clear sky direct normal irradiance criteria. In addition, to eliminate very hazy skies or conditions of high thin cloud cover, we also require that the ratio of diffuse to global irradiance be less than 0.67. The plot shows substantial monthly variation, which reflects the wide range of seasonal atmospheric conditions. The 200 W/m² curve, based on our measured data, closely approximates the long-term NOAA data for San Francisco, as shown by the figure. The criterion of 400 W/m² as an indicator of sunshine appears to be too severe.

We summarize the monthly frequency of type of sky condition in Fig. 17. The overcast definition requires $E_{esn} < 20 \text{ W/m}^2$ and diffuse/global irradiance > 0.67 . The clear sky definition is $E_{esn} > 200 \text{ W/m}^2$ and diffuse/global irradiance < 0.67 . Only 10-15% of total sky conditions lie outside these nominal sky types. These definitions are convenient for numerical processing of large quantities of measured data, but they hide the fact that both "overcast" and "clear" include a wide range of cloud cover and atmospheric conditions. Further testing of our data set is in progress to determine if other definitions of sky types might more usefully disaggregate the total data set.

SUMMARY AND CONCLUSIONS

From measurements of solar radiation and daylight taken during four years in downtown San Francisco, we have calculated maximum and minimum levels of illuminance and irradiance for clear sky conditions. The effect of ground reflectance was measured and found to differ for clear and for overcast days. Empirical fits were presented for predicting clear (global, diffuse) and overcast sky illuminance and irradiance as functions of solar altitude. Hourly and monthly average illuminance data for horizontal and vertical surfaces have been presented as isolux contour plots, which can be used directly in building design to predict the time periods for which average illuminance will exceed some specified value. We also computed the probability of exceeding specified illuminance or irradiance values on horizontal and vertical surfaces. These data are useful in predicting the performance of lighting control systems keyed to a calculation of horizontal or vertical daylight factor. Average sunshine probability data for our measurement period follow the trend of the long-term NOAA data if the ratio of diffuse to global irradiance is used as a criterion in addition to $E_{esn} > 200 \text{ W/m}^2$. For the clear and overcast sky criteria used in this study, only 10-15% of the total data set lies outside either of the standard sky conditions.

The four years of data analyzed show substantial month-to-month variation between years, and smaller but significant variation on an average annual basis. This finding emphasizes the need for long-term data collection and analysis and suggests that availability predictions based on short-term data collection (one or two years) may not be representative of long-term conditions. Additional analysis of the dependence of clear sky illuminance on turbidity and equations for predicting zenith luminance values are contained in companion papers [10, 11].

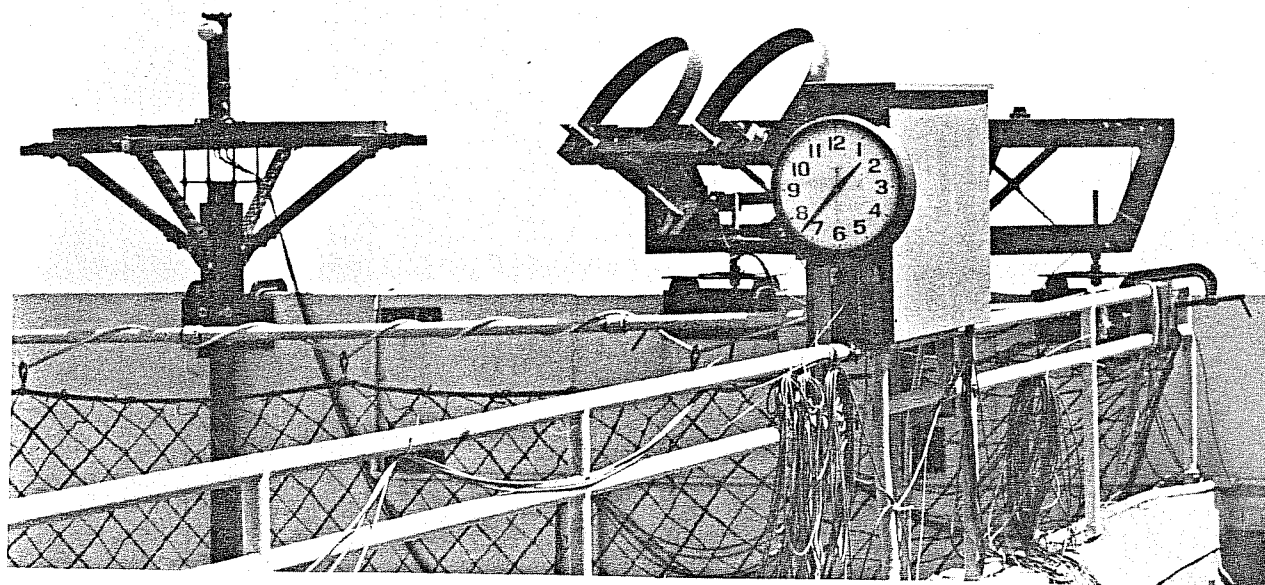
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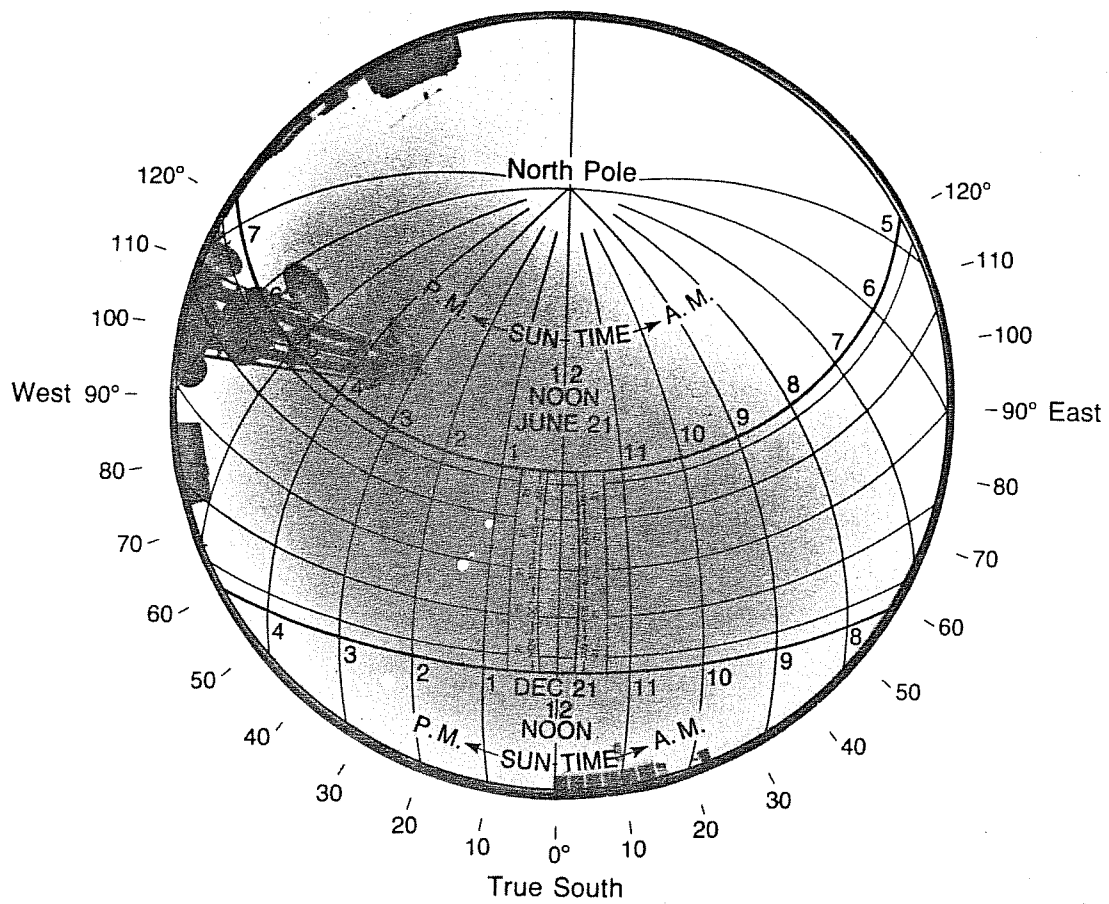
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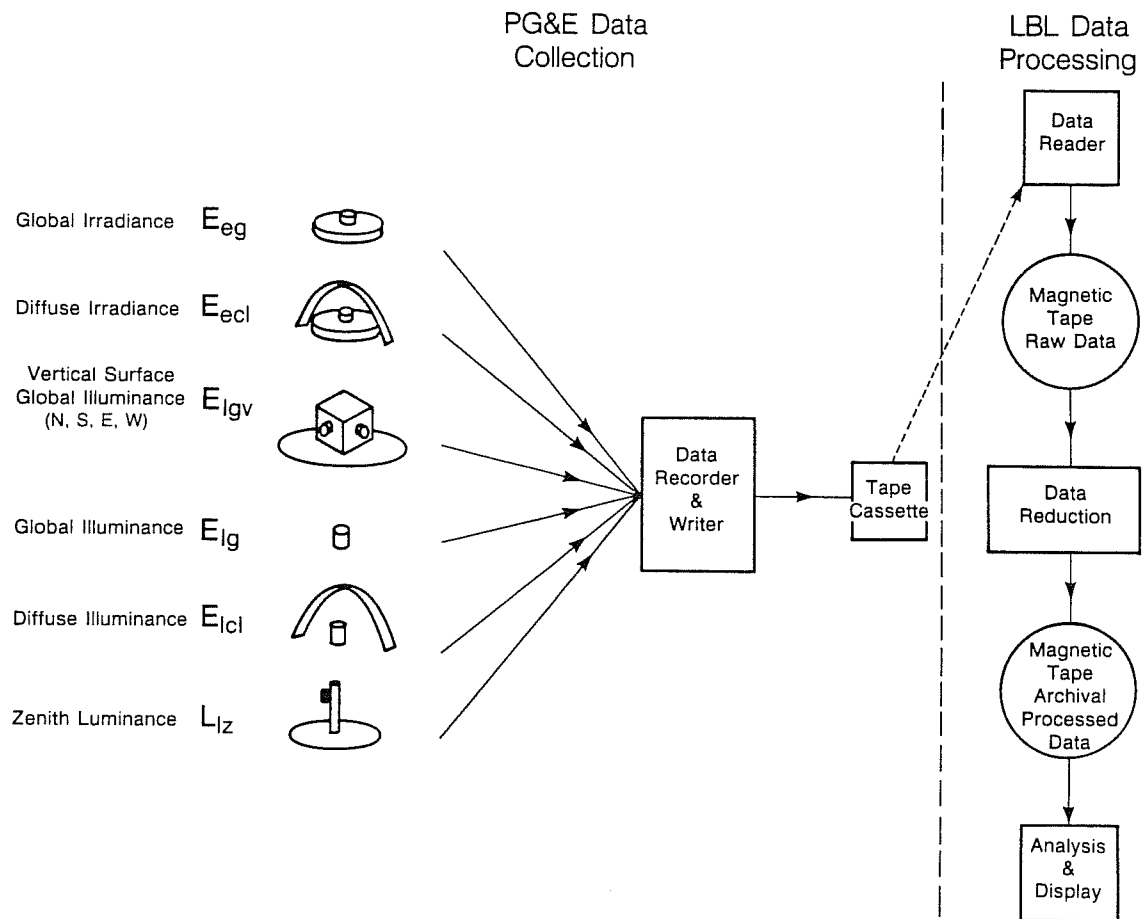
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Figure 1 - View of photometric and radiometric instrumentation on the roof of the Pacific Gas and Electric building in downtown San Francisco.



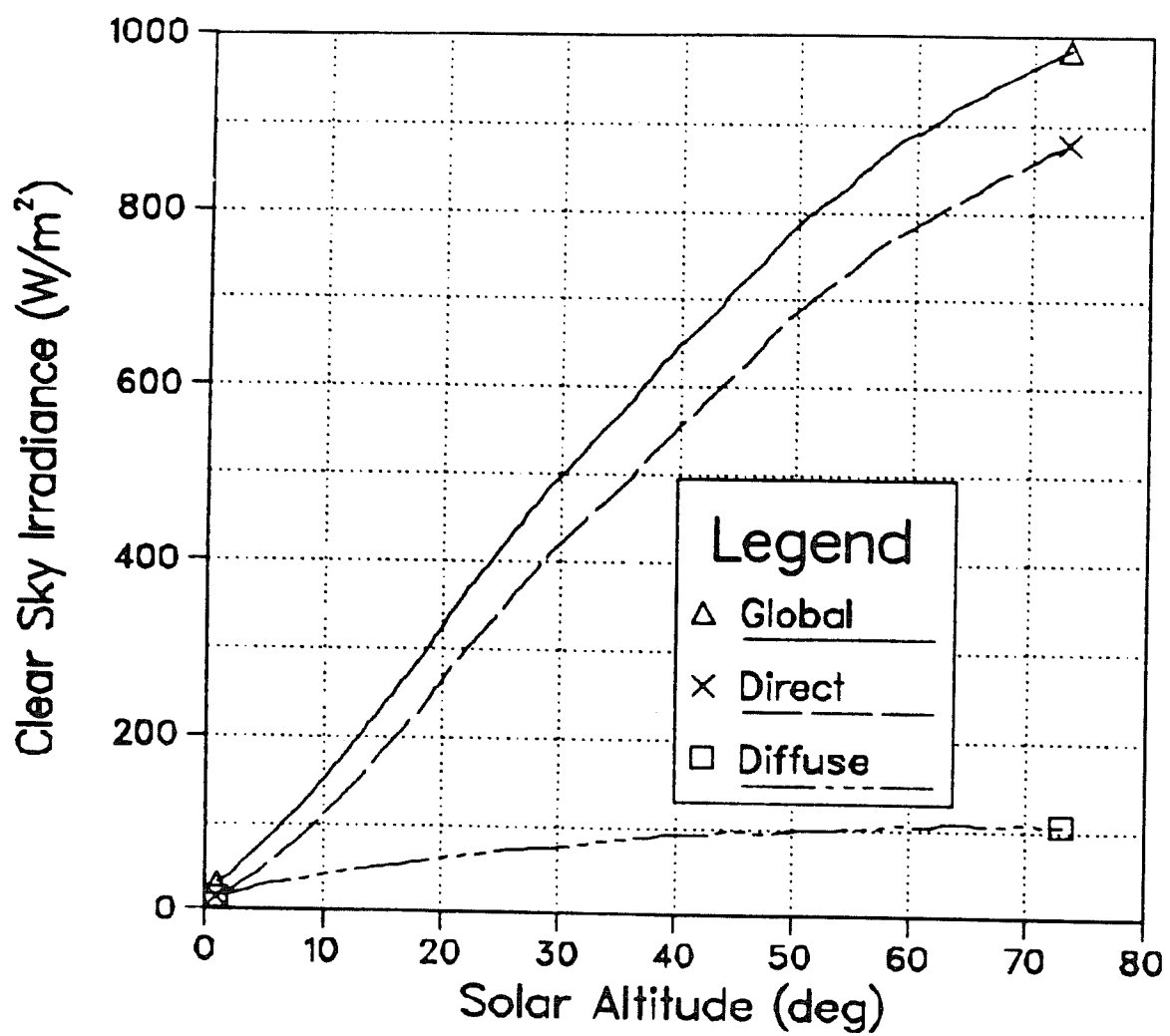
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Figure 2 - 180° fisheye view looking up at instrument location, showing sky obstructions.



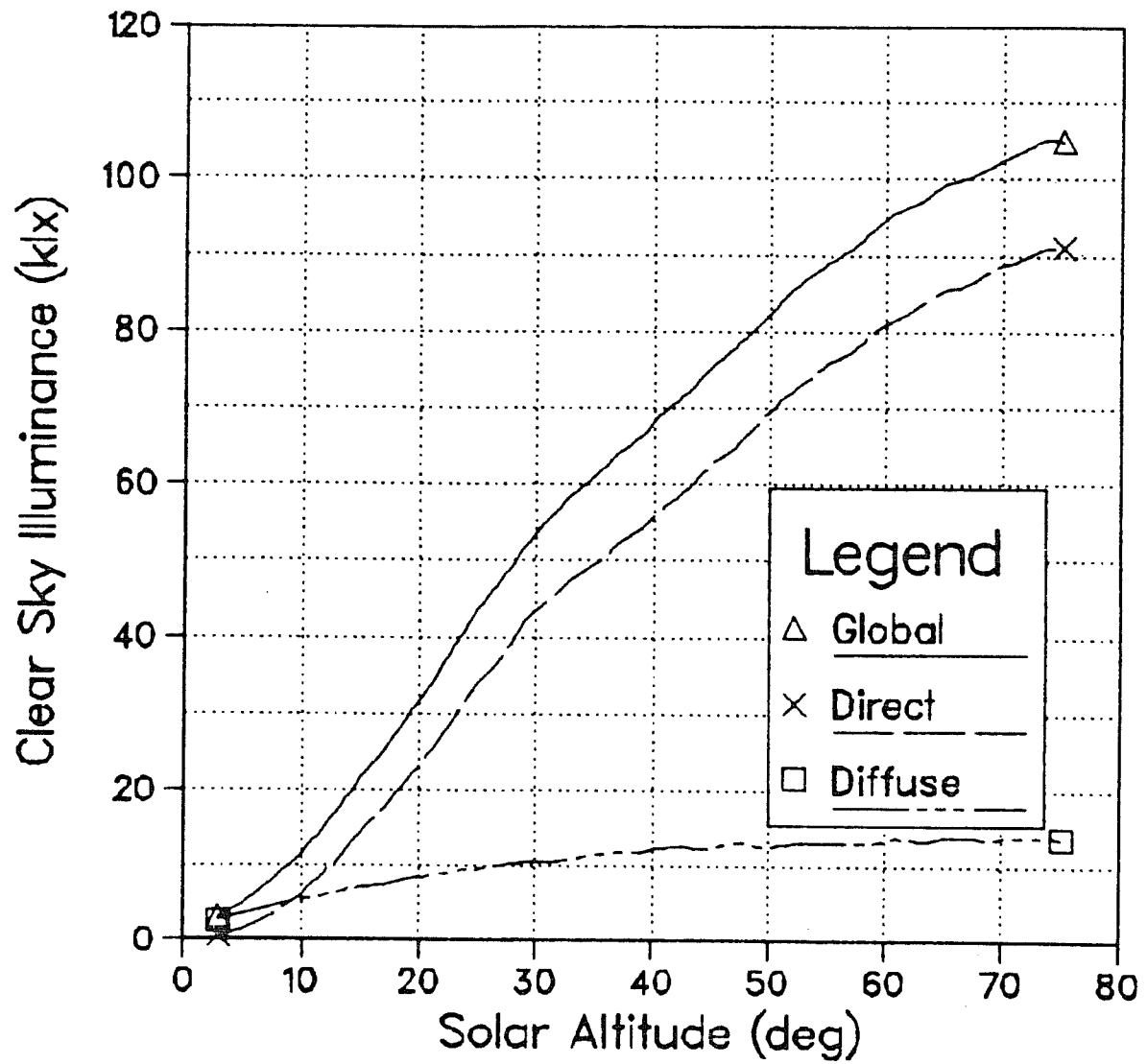
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Figure 3 - Data flow from sensors to archival data base at LBL.



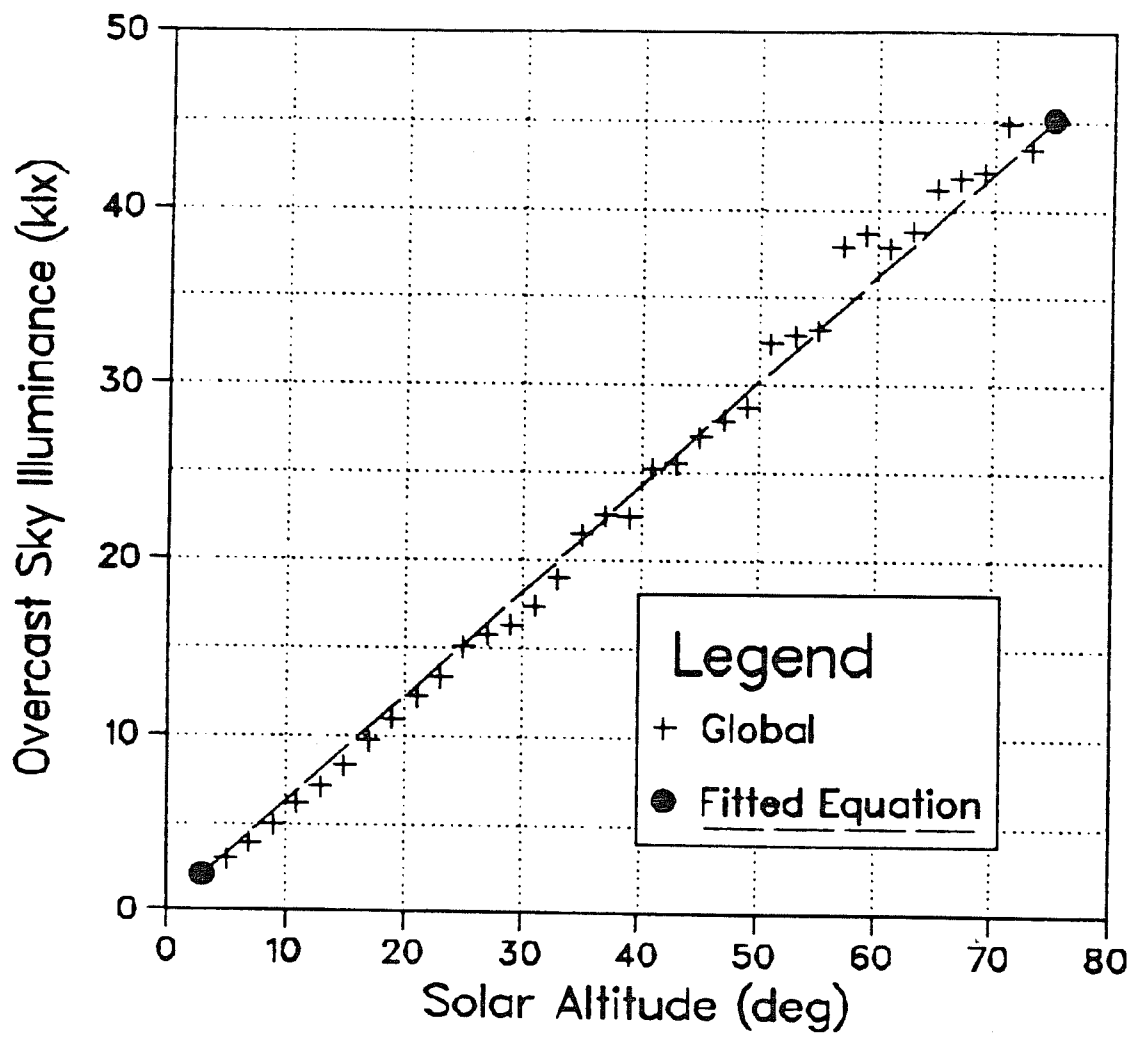
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Figure 4 - Clear sky irradiance on a horizontal surface (global, direct, and diffuse) as a function of solar altitude.



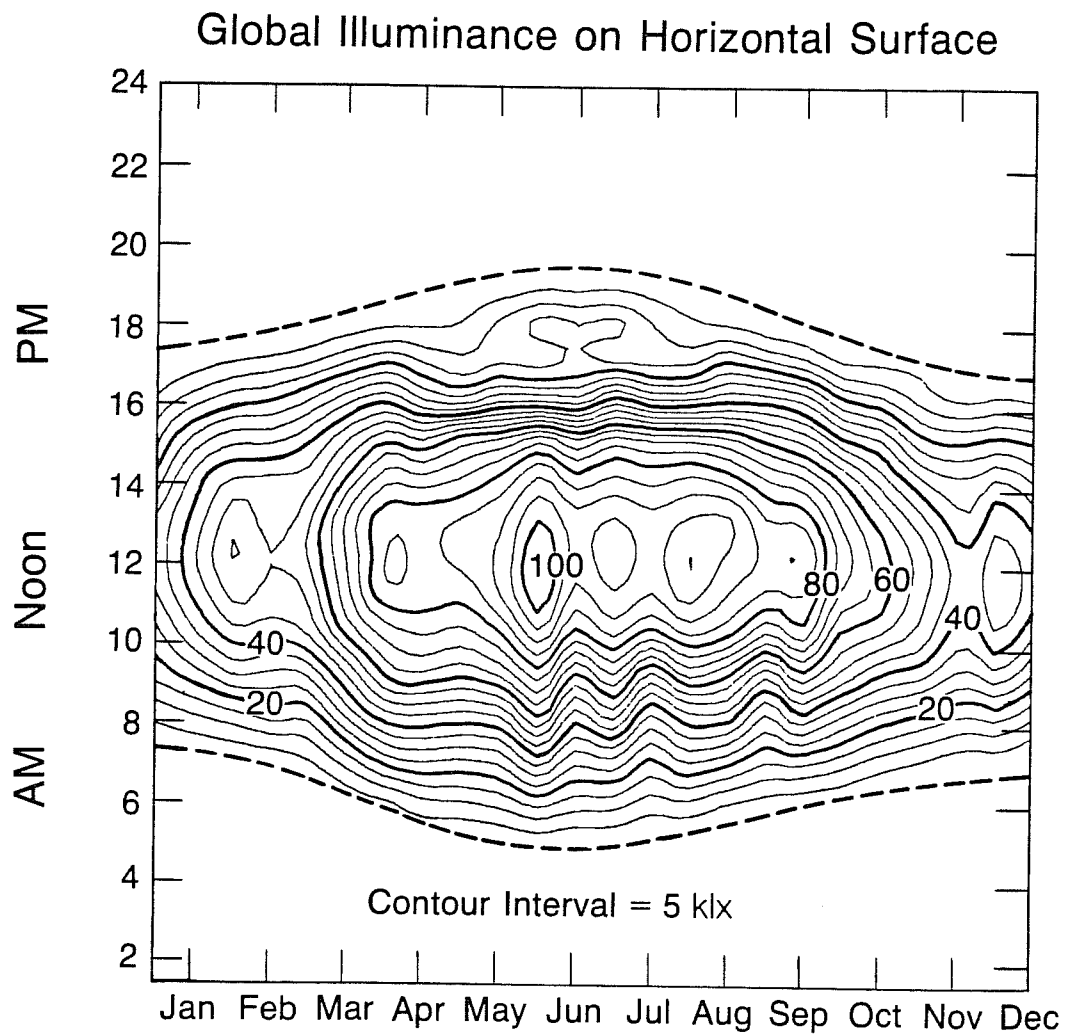
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Figure 5 - Clear sky illuminance on a horizontal surface (global, direct, and diffuse) as a function of solar altitude.



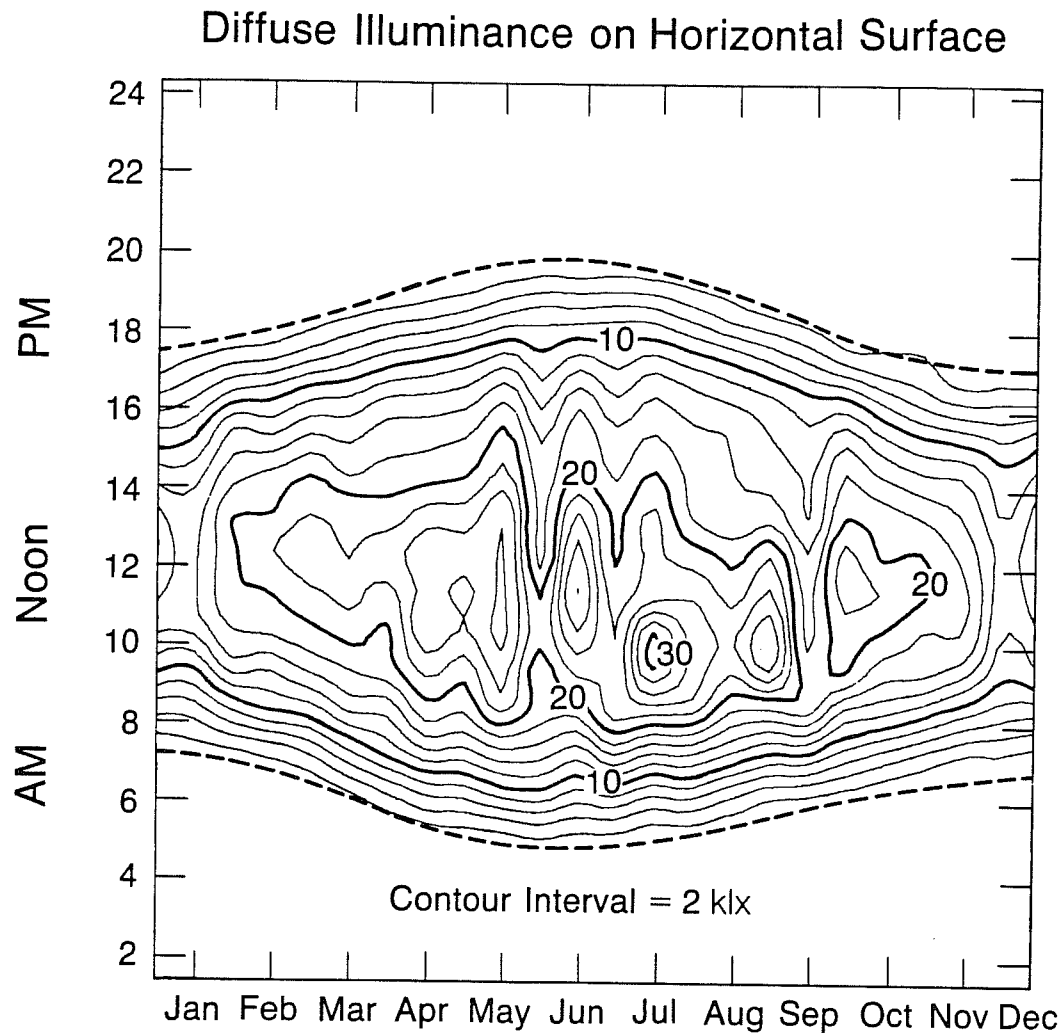
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Figure 6 - Overcast sky illuminance on a horizontal surface as a function of solar altitude.



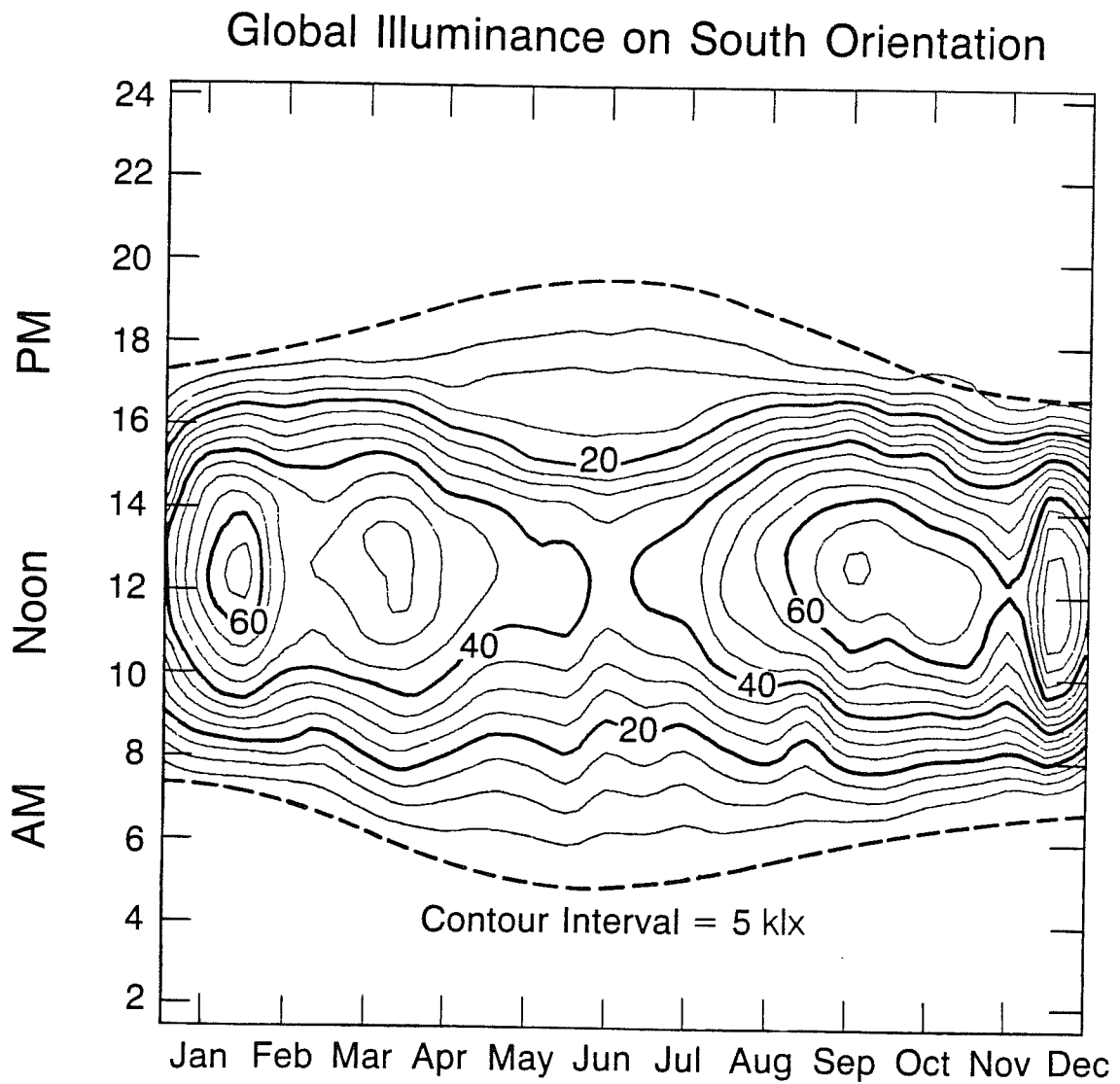
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Figure 7 - Isolux contours of global horizontal illuminance.



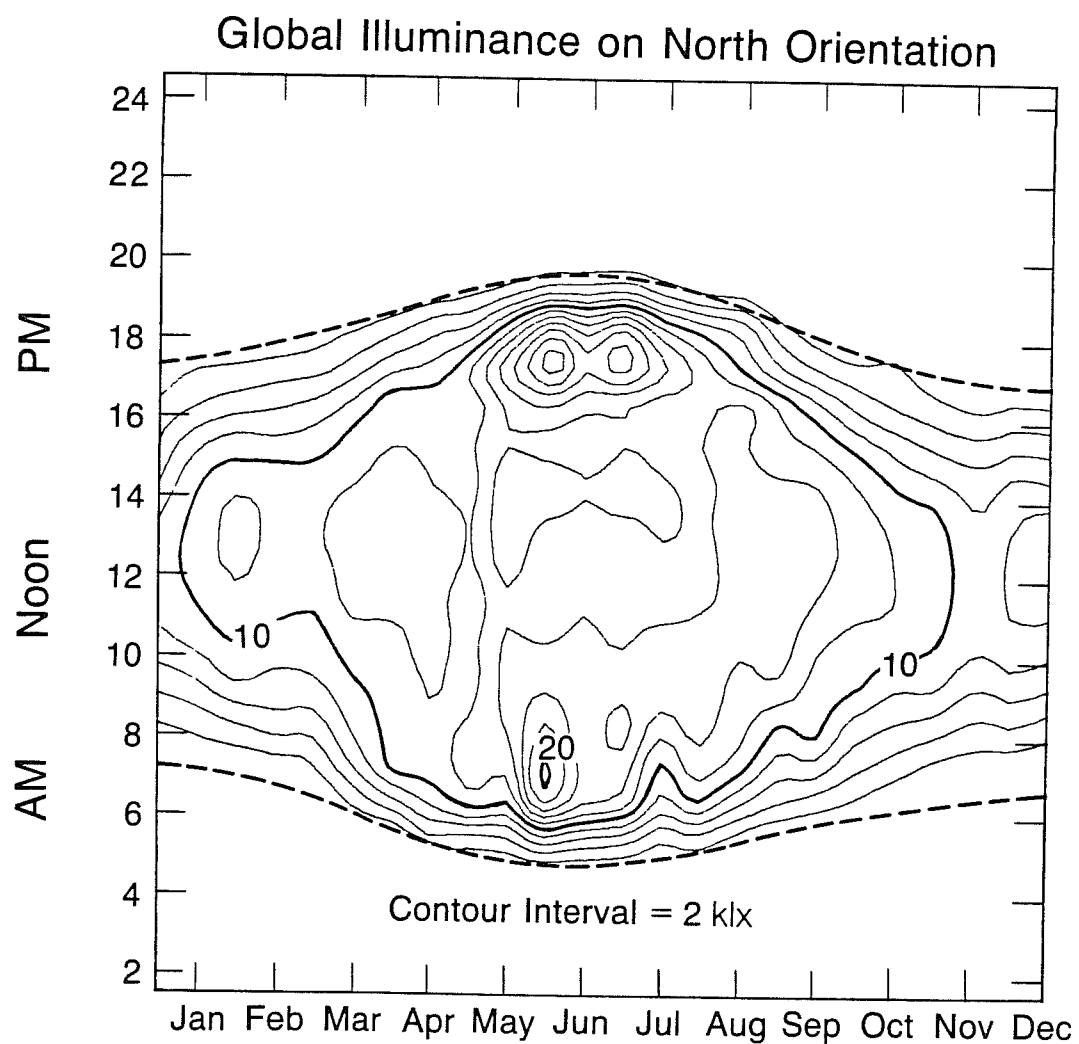
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Figure 8 - Isolux contours of diffuse horizontal illuminance.



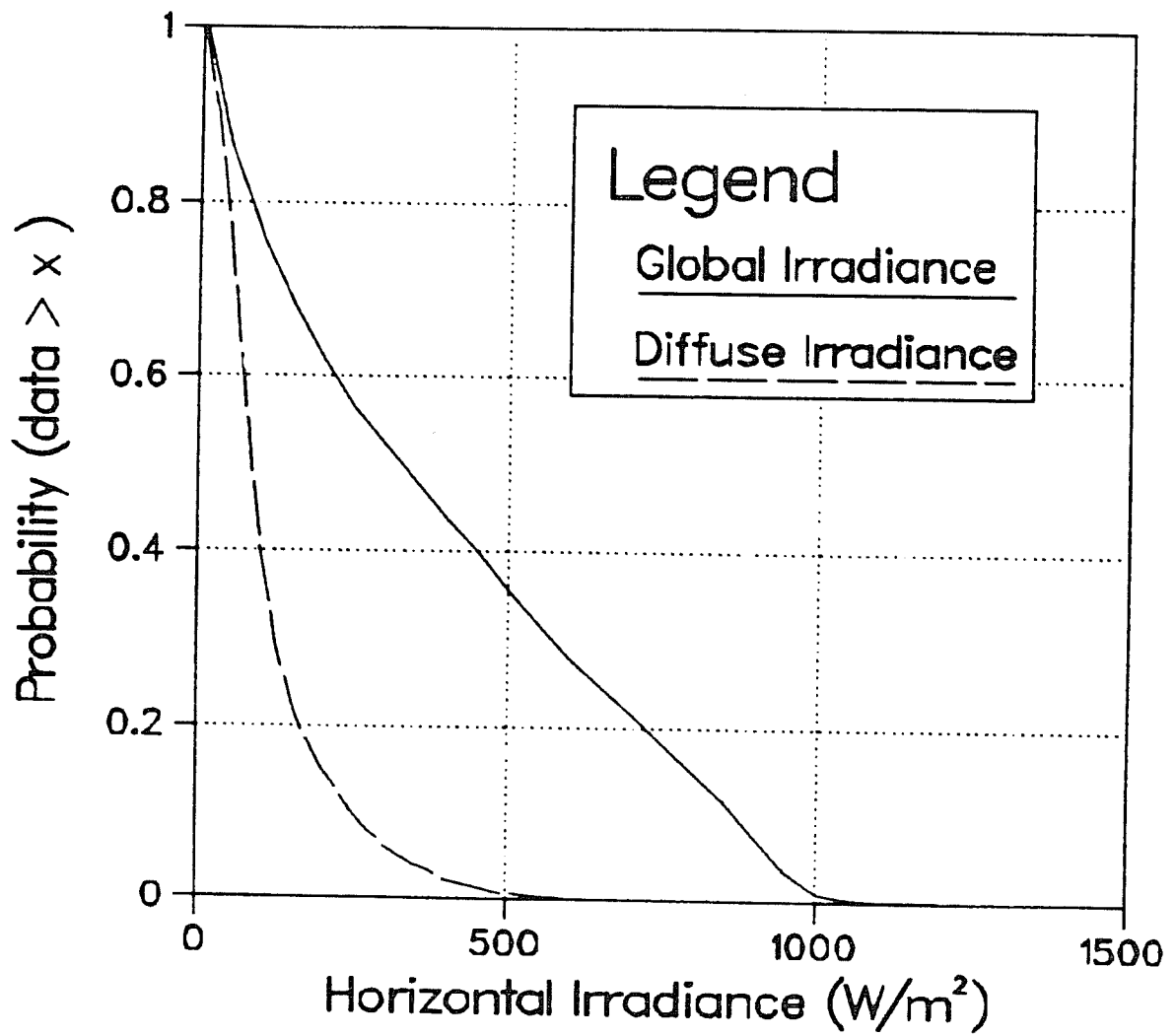
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Figure 10 - Isolux contours of global vertical illuminance (south).



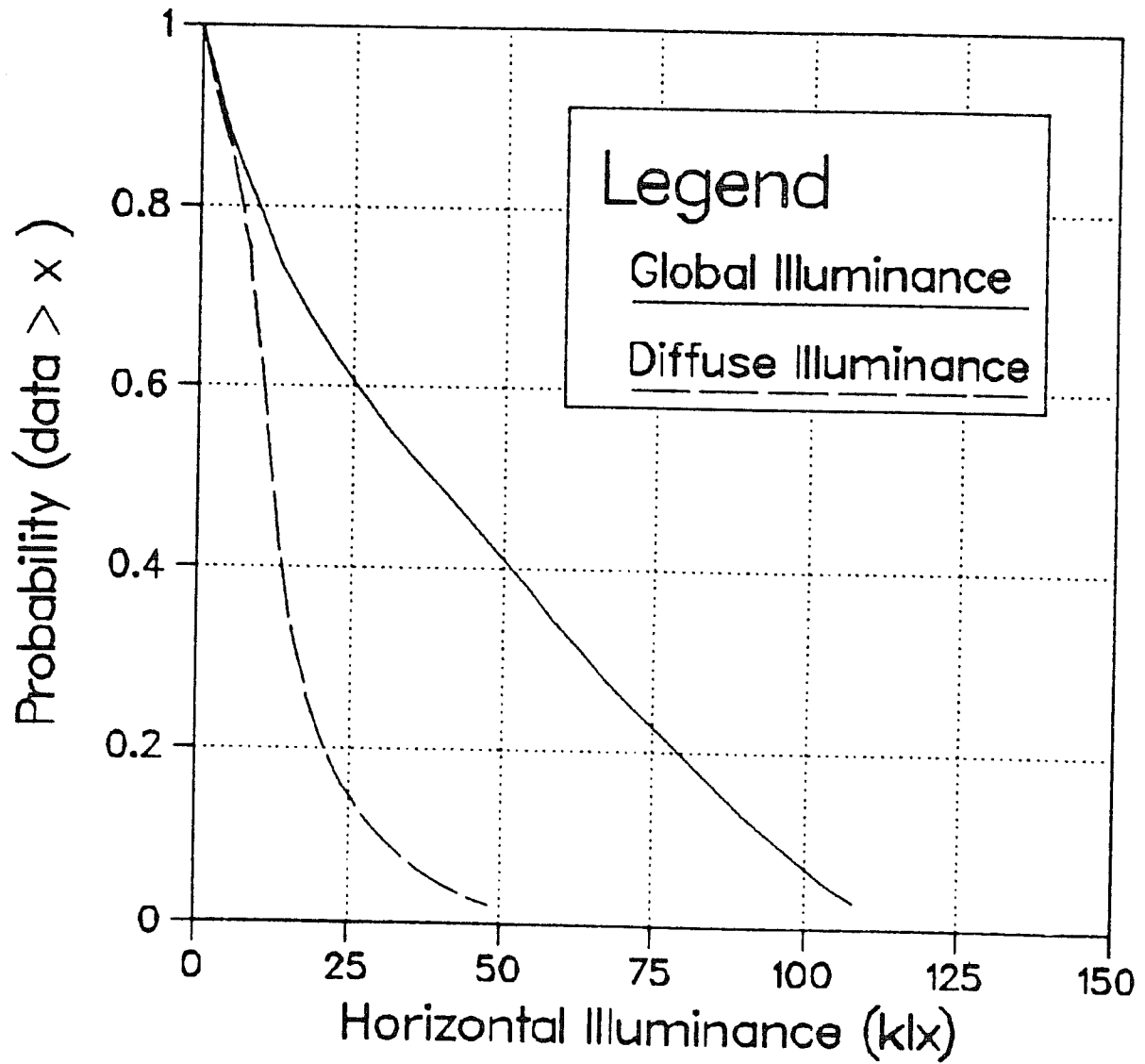
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Figure 11 - Isolux contours of global vertical illuminance (north).



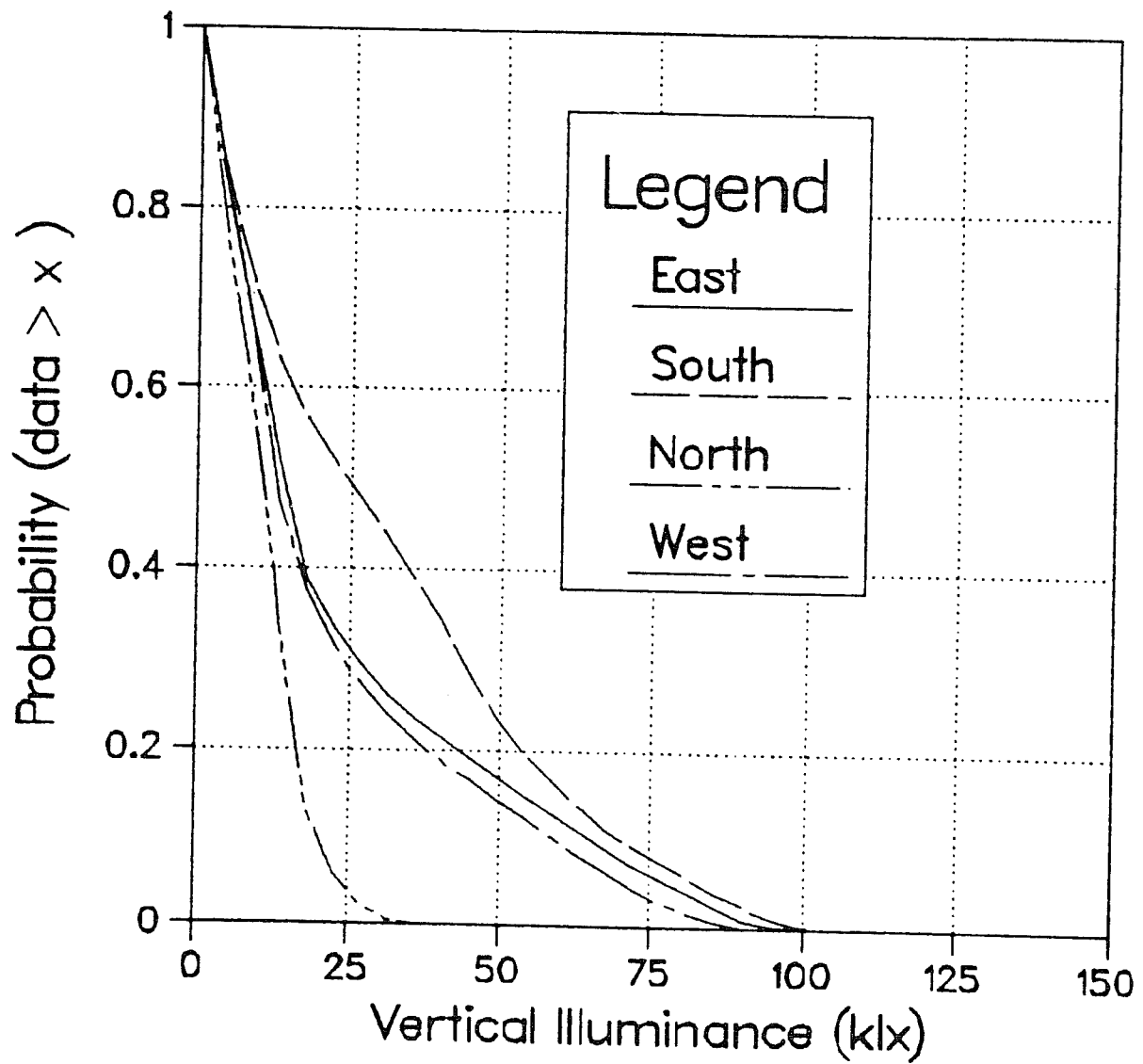
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Figure 13 - Probability distribution of irradiance on a horizontal surface (global and diffuse).



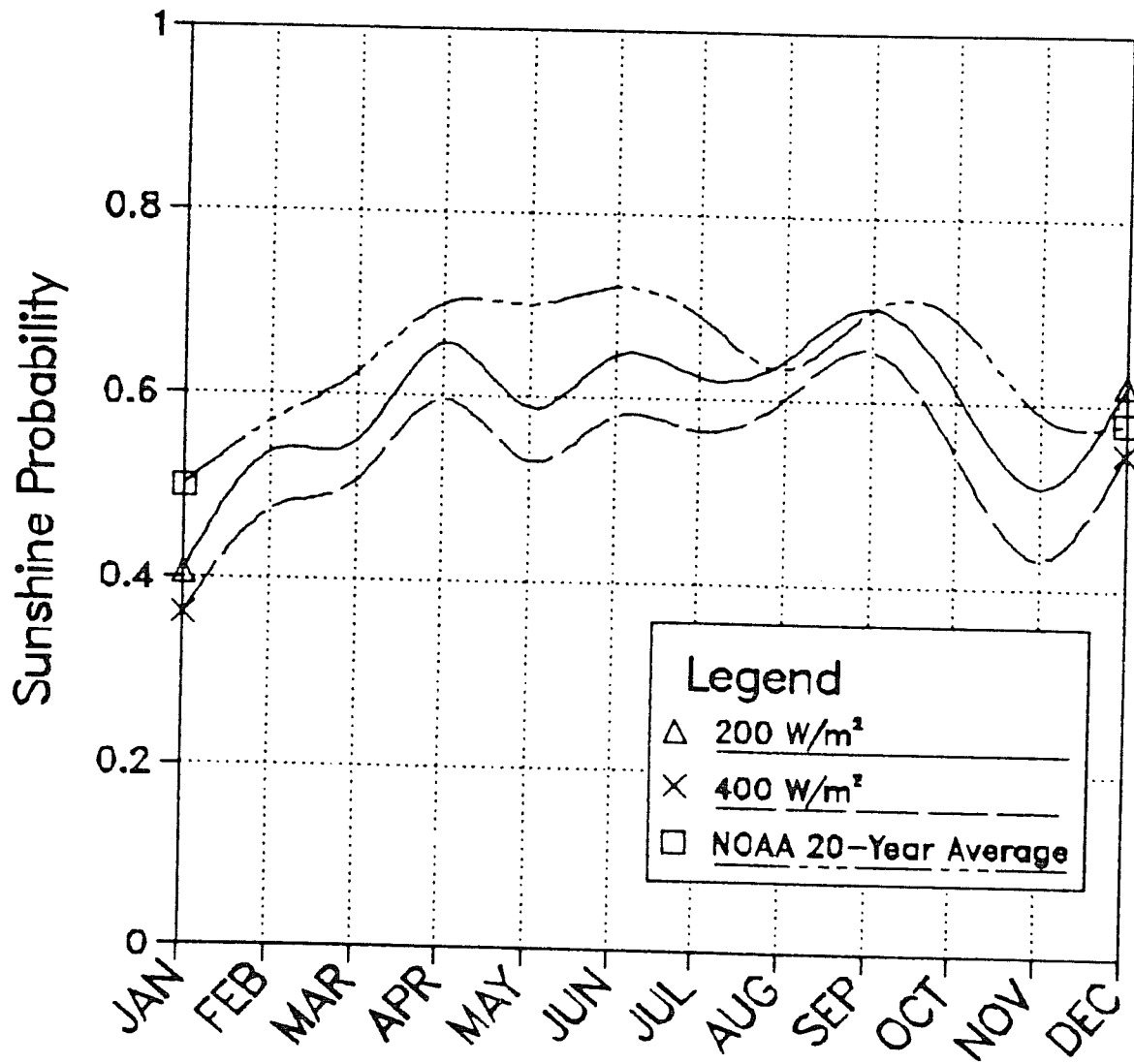
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Figure 14 - Probability distribution of illuminance on a horizontal surface (global and diffuse).



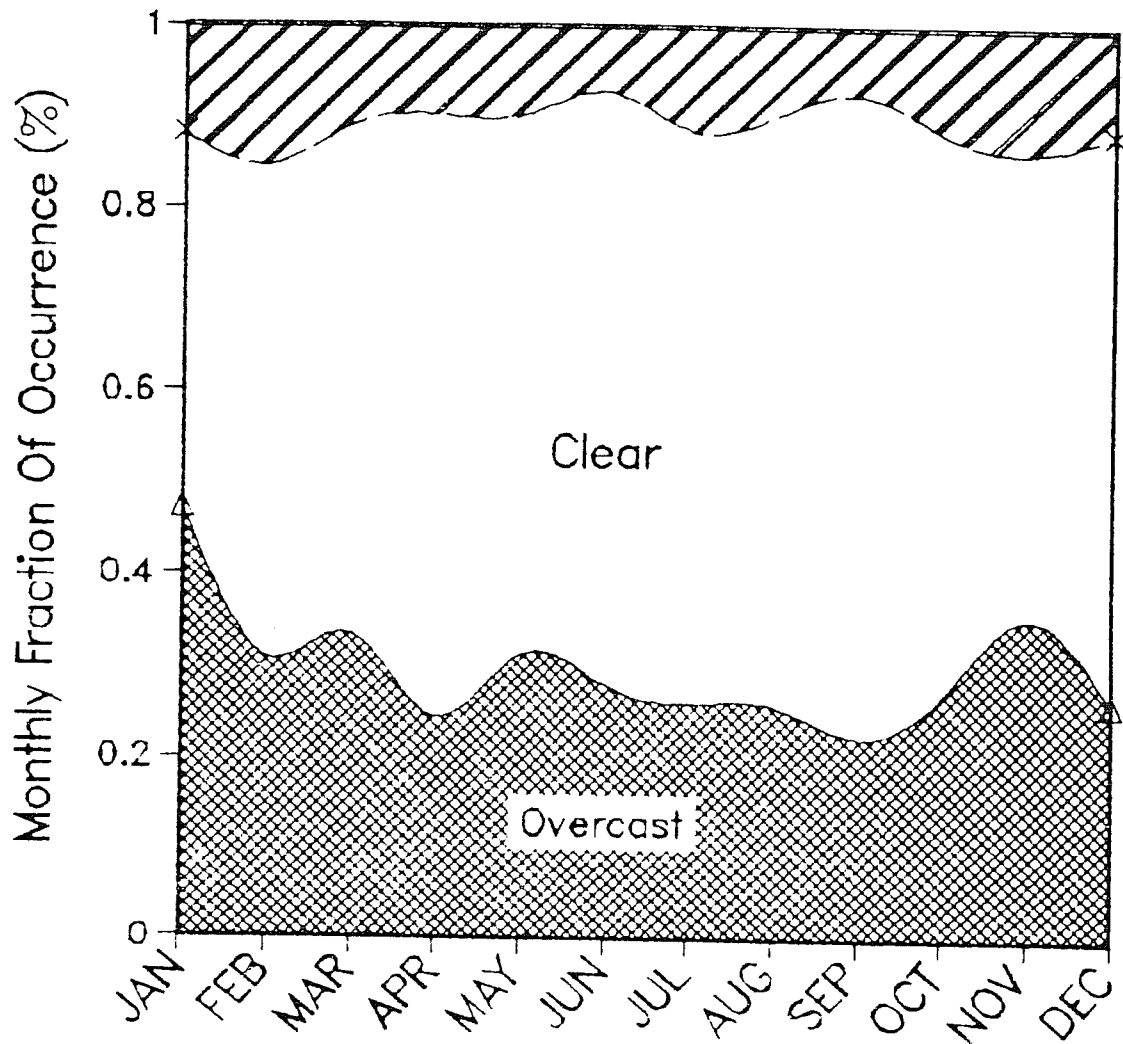
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Figure 15 - Probability distribution of global illuminance on a vertical surface (North, South, East, and West).



XBL 845-2039

Figure 16 - Monthly sunshine probability based on long-term NOAA data and for two cases of minimum E_{esn} to define "sunshine" condition. In both cases we also require the ratio of diffuse to global irradiance to be less than 2/3.



XBL 845-2040

Figure 17 - Monthly fraction of clear, overcast, and other sky conditions. Criteria for each day type are explained in text.